Pulse Width Modulation Control of a Direct AC-AC Power Converter with Five-phase Input and Three-phase Output

Sk. Moin. Ahmed, H. Abu-Rub, A. Iqbal*

Department of Electrical & Computer Engineering, Texas A&M University at Qatar, Doha, Qatar

*Department of Electrical Engineering, College of Engineering, Qatar University, Qatar

Emails: moin.sk@qatar.tamu.edu; haitham.abu-rub@qatar.tamu.edu; atif.iqbal@qu.edu.qa

Abstract

This paper presents pulse width modulation technique for a direct ac-ac converter. The converter has five-phase input supply and three-phase output. The input supply may be obtained from a five-phase wind energy generation system with variable output voltage magnitude and frequency. The output of the proposed converter topology may be fed to the three-phase stiff grid system. Thus the requirement of the modulation of the ac-ac converter is to produce fixed voltage and fixed frequency output while the input can be variable. Additionally the output voltage gain should be high. Simple carrier-based PWM technique is suggested and harmonic injection scheme is proposed to enhance the output voltage magnitude. The output voltage reaches 89.2% of the input supply voltage with the proposed technique. An additional control block is used to stabilize the output voltage and frequency of the converter. Simulation and experimental results are shown in the paper for the verification of the proposed scheme.

Keywords

Matrix Converter; Five-phase; Carrier based; Pulse Width Modulation

Introduction

Multi-phase drive systems have been widely investigated in the literature and their reviews are presented in [1]. Multi-phase drive systems are shown to offer several advantages when compared with the three-phase drive system. This is possible due to the advanced development of the modern power electronic converters. The increased penetration of renewable energy generation especially wind energy generation system requires more robust, reliable and high power density generation system. The use of multi-phase generation system for renewable energy is reported recently [2-12]. Since the multi-phase machines offer the advantages of high reliability and high power density, they can be ideal choice of wind energy generation system. Normally, the interfacing of the renewable energy sources with the grid is done using a power electronic converter. Matrix converters are normally employed in the wind generation system to stabilize the voltage and frequency for grid integration [13-16].

The matrix converter or direct ac-ac converter offers several advantages over back-to-back bidirectional converters. The back-to-back converter offer bidirectional power flow by using fewer numbers of power switching devices and that too by using unidirectional IGBTs. However, the requirement of bulky dc link capacitor cannot be avoided. Moreover, the back-to-back converter needs extra feedback current control loop for controlling rectifier d-q axis current and also voltage control loop for controlling dc link voltage. Additionally, the matrix converter topology has the capability of providing active damping by injecting reactive power. The back-to-back converter has a limitation of reactive power injection due to limited component ratings. Further comparison can be done by looking at the per switch output current and it is lower in the case of matrix converter and thus is better suited for high current start-up applications and for continuous low frequency operation.

A five-to-three-phase matrix converter topology is proposed in [17-18] for use in variable speed drives application. The proposed PWM technique in [17] is based on space vector PWM and the PWM reported in [18] is based on carrier-based scheme. The output voltage limit is not studied in these papers. Moreover, the output voltage is intended to have variable voltage and variable frequency. In contract this paper focuses on obtaining fixed voltage and fixed frequency output for variable voltage and variable frequency input.

This paper proposes modulation and control techniques for a matrix converter with five-phase input and three-phase output. This matrix converter topology is intended to use for a five-phase wind energy generation system. The major advantage of the proposed matrix converter is high output voltage value when compared to a conventional three-phase to three-phase output matrix converter. The output is limited to 86.6% in the conventional three-phase input to three-phase output matrix converter. This value is 89.2% in the matrix converter with five-phase input and three-phase output. However, this limit can be further enhanced by employing over-modulation and at the cost of introducing low-order harmonics in the output. The block diagram of the proposed system is shown in Fig. 1. This paper focuses on the pulse width modulation control of the matrix converter part only.

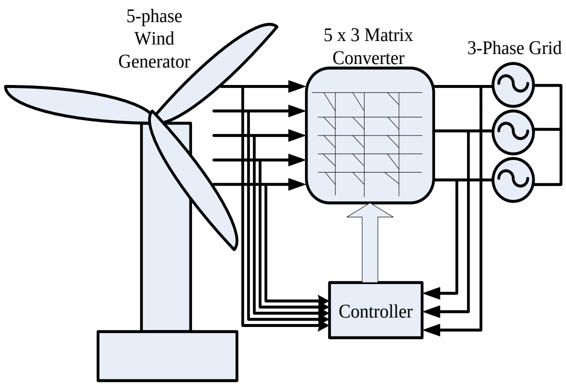

FIG. 1 BLOCK SCHEMATIC OF THE SYSTEM UNDER INVESTIGATION

Pwm of 5 x 3 matrix converter

The input five-phase system is assumed as.

$$v_a = |V|\cos(\omega t), \quad v_b = |V|\cos(\omega t - 2\pi/5),$$
$$v_c = |V|\cos(\omega t - 4\pi/5), \quad v_d = |V|\cos(\omega t + 4\pi/5) \tag{1}$$
$$v_e = |V|\cos(\omega t + 2\pi/5)$$

Since the matrix converter outputs voltages with frequency decoupled from the input voltages, the duty ratios of the switches are to be calculated accordingly. The three-phase output voltage duty ratios should be calculated in such a way that output voltages remains independent of input frequency. In other words, the three-phase output voltages can be considered in synchronous reference frame and the five-phase input voltages can be considered to be in stationary reference frame, so that the input frequency term will be absent in output voltages. Considering the above, duty ratios of output phase *j* is chosen as

$$\begin{aligned} &\delta_{aj} = k_j\cos(\omega t - \rho), \delta_{bj} = k_j\cos(\omega t - 2\pi/5 - \rho), \\ &\delta_{cj} = k_j\cos(\omega t - 4\pi/5 - \rho)\delta_{dj} = \\ &k_j\cos(\omega t + 4\pi/5 - \rho), \\ &\delta_{ej} = k_j\cos(\omega t + 2\pi/5 - \rho) \end{aligned} \tag{2}$$

The input and output voltages are related as:

$$\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = \begin{bmatrix} \delta_{aA} & \delta_{bA} & \delta_{cA} & \delta_{dA} & \delta_{eA} \\ \delta_{aB} & \delta_{bB} & \delta_{cB} & \delta_{dB} & \delta_{eB} \\ \delta_{aC} & \delta_{bC} & \delta_{cC} & \delta_{dC} & \delta_{eC} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \\ v_d \\ v_e \end{bmatrix} \tag{3}$$

Therefore the phase *j* output voltage can be obtained by using the above duty ratios as

$$\begin{aligned} V_j = k_j|V|[&\cos(\omega t)\bullet\cos(\omega t - \rho) + \cos(\omega t - 2\pi/5) \\ &\bullet\cos(\omega t - 2\pi/5 - \rho) + \cos(\omega t - 4\pi/5) \\ &\bullet\cos(\omega t - 4\pi/5 - \rho) + \cos(\omega t + 4\pi/5) \\ &\bullet\cos(\omega t + 4\pi/5 - \rho) + \cos(\omega t + 2\pi/5) \\ &\bullet\cos(\omega t + 2\pi/5 - \rho)] \end{aligned} \tag{4}$$

In general equation (4) can be written as

$$V_j = \frac{5}{2}k_j|V|\cos(\rho) \tag{5}$$

In eq (5), $\cos(\rho)$ term indicates that the output voltage is affected ρ. Thus, the output voltage V_j is independent of the input frequency and only depends on the amplitude $|V|$ of the input voltage and k_j is a reference output voltage time-varying modulating signal for the output phase *j* with the desired output frequency ω_o. The three phase reference output voltages can be represented as

$$\begin{aligned} &k_A = m\cos(\omega_o t), k_B = m\cos(\omega_o t - 2\pi/3), k_C = \\ &m\cos(\omega_o t - 4\pi/3) \end{aligned} \tag{6}$$

Therefore, from (5), the output voltages are obtained as;

$$\begin{aligned} &V_A = \left[\frac{5}{2}m|V|\cos(\rho)\right]\cos(\omega_o t), V_B = \left[\frac{5}{2}m|V|\cos(\rho)\right] \\ &\cos(\omega_o t - 2\frac{\pi}{3}), V_C = \left[\frac{5}{2}m|V|\cos(\rho)\right]\cos(\omega_o t - 4\frac{\pi}{3}) \end{aligned} \tag{7}$$

Application of Offset Duty Ratio

In the above discussion, duty-ratios become negative (see eq. (6)) which are not practically realizable. For the switches connected to output phase-*j*, at any instant, the condition $0 \le d_{aj}, d_{bj}, d_{cj}, d_{dj}, d_{ej} \le 1$ and

$d_{aj} + d_{bj} + d_{cj} + d_{dj} + d_{ej} = 1$ Should be valid. Therefore, offset duty ratios should to be added to the existing duty-ratios, so that the net resultant duty-ratios of individual switches are always positive. Furthermore, the offset duty-ratios should be added equally to all the output phases to ensure that the effect of resultant output voltage vector produced by the offset duty-ratios is null in the load. That is, the offset duty-ratios can only add the common-mode voltages in the output. Considering the case of output phase-*j*;

$$\begin{aligned} d_{aj} + d_{bj} + d_{cj} + d_{dj} + d_{ej} &= k_j \cos(\omega t - \rho) + k_j \\ &\cos(\omega t - 2\pi/5 - \rho) + k_j \cos(\omega t - 4\pi/5 - \rho) \\ &+ k_j \cos(\omega t + 4\pi/5 - \rho) \\ &+ k_j \cos(\omega t + 2\pi/5 - \rho) = 0 \end{aligned} \tag{8}$$

The sum of all the duty ratios is zero because the duty ratios contain equal amount of positive and negative components. Absolute values of the duty-ratios are added to cancel the negative components from individual duty ratios. Thus the minimum individual offset duty ratios should be

$$\begin{aligned} D_a(t) &= |d_{aj}| = |k_j \cos(\omega t - \rho)|, \\ D_b(t) &= |d_{bj}| = |k_j \cos(\omega t - 2\pi/5 - \rho)|, \\ D_c(t) &= |d_{cj}| = |k_j \cos(\omega t - 4\pi/5 - \rho)|, \\ D_d(t) &= |d_{dj}| = |k_j \cos(\omega t + 4\pi/5 - \rho)|, \\ D_e(t) &= |d_{dj}| = |k_j \cos(\omega t + 2\pi/5 - \rho)| \end{aligned} \tag{9}$$

The effective duty ratios are

$$\begin{aligned} &\delta'_{aj} = d_{aj} + D_a(t), \delta'_{bj} = d_{bj} + D_b(t), \delta'_{cj} = d_{cj} + D_c(t), \\ &\delta'_{dj} = d_{dj} + D_d(t), \delta'_{ej} = d_{ej} + D_e(t) \end{aligned} \tag{10}$$

The net duty ratios $0 \le \delta'_{aj}, \delta'_{bj}, \delta'_{cj}, \delta'_{dj}, \delta'_{ej} \le 1$ should be within the range of 0 to 1.

For the worst case in respect of five phase input

$$0 \le 2.|k_j| \times 2\cos(pi/5) \le 1 \tag{11}$$

The maximum value of k_j is equal to 0.309 or *sin(pi/10)*. In any switching cycle the output phase should not be open circuited. Thus the sum of the duty ratios in (9) must equal unity. But the summation $D_a(t) + D_b(t) + D_c(t) + D_d(t) + D_e(t)$ is less than or equal to unity. Hence another offset duty-ratio $[1 - \{D_a(t) + D_b(t) + D_c(t) + D_d(t) + D_e(t)\}]/5$ is added to $D_a(t), D_b(t), D_c(t), D_d(t)$ *and* $D_e(t)$ in (11). The addition of this offset duty-ratio in all switches will maintain the output voltages and input currents unaffected. The above explanation finally derives the maximum modulation index for five phase input with three phase output from equation (7) as

$$\frac{5}{2} k_j = \frac{5}{2} \times \sin(\frac{\pi}{10}) = 0.7725 \text{ or } 77.25\%$$

If k_A, k_B, k_C are chosen to be 3-phase sinusoidal references as given in equation (6), the input voltage capability is not fully utilized for output voltage generation and the output magnitude remains only 77.25% of the input magnitude. To overcome this, an additional common mode term equal to $\{\max(k_A, k_B, k_C) + \min(k_A, k_B, k_C)\}/2]$ is added as in the carrier-based PWM principle as implemented in two-level inverters. Thus the amplitude of (k_A, k_B, k_C) can be enhanced from 0.309 to 0.3568.

Without Common-mode voltage addition

In the above section 2.1, two offsets are added to the original duty ratios to form the following effective duty ratio that can be compared to the triangular carrier wave to generate the gating signals for the bidirectional power switches. The output phase voltage magnitude will reach 77.25% of the input voltage magnitude with this method. To further enhance the output voltage magnitude, common mode voltage of the output reference signals are added to formulate the new duty ratios as discussed in the next section.

With Common mode voltage Addition

The duty ratios can further be modified by injection common mode voltage of the output voltage references to improve the output voltage magnitude. The output voltage magnitude increases and reaches its limiting value of 89.2% of the input magnitude. The common mode voltage that is added to obtain new duty ratios are;

$$V_{cm} = -\frac{V_{Max} - V_{Min}}{2} \qquad (12)$$

Where

$$V_{MAX} = max\{k_A, k_B, k_C\}, V_{MIN} = min\{k_A, k_B, k_C\} \qquad (13)$$

The duty ratio for output phase p can be written as;

$$\begin{aligned}
\delta_{aj} &= D_a(t) + (1 - \{D_a(t) + D_b(t) + D_c(t) + D_d(t) \\
&+ D_e(t)\})/3 + \left[k_j + V_{cm}\right] \times \cos(\omega t - \rho) \\
\delta_{bj} &= D_b(t) + (1 - \{D_a(t) + D_b(t) + D_c(t) + D_d(t) \\
&+ D_e(t)\})/3 + \left[k_j + V_{cm}\right] \times \cos(\omega t - 2\pi/5 - \rho) \\
\delta_{cj} &= D_c(t) + (1 - \{D_a(t) + D_b(t) + D_c(t) + D_d(t) \\
&+ D_e(t)\})/3 + \left[k_j + V_{cm}\right] \times \cos(\omega t - 4\pi/5 - \rho) \\
\delta_{dj} &= D_d(t) + (1 - \{D_a(t) + D_b(t) + D_c(t) + D_d(t) \\
&+ D_e(t)\})/3 + \left[k_j + V_{cm}\right] \times \cos(\omega t + 4\pi/5 - \rho) \\
\delta_{ej} &= D_e(t) + (1 - \{D_a(t) + D_b(t) + D_c(t) + D_d(t) \\
&+ D_e(t)\})/3 + \left[k_j + V_{cm}\right] \times \cos(\omega t + 2\pi/5 - \rho)
\end{aligned} \qquad (14)$$

Where $j \in A, B, C$

Simulation Results

The proposed scheme is validated by simulation of five to three phase Matrix converter using Matlab/Simulink. The model is simulated for five phase input at 40Hz with 100V peak per phase. With this constraint the model is simulated for 30millisec or 0.03sec, then the input frequency is changed to 60 Hz and also the voltage peak is changed to 120V and the model is run for another 0.03sec. The output Voltages have constant frequency and constant voltage for all the time of simulation. Different simulation results are shown in the figures. The practical implementation of the proposed scheme is under study.

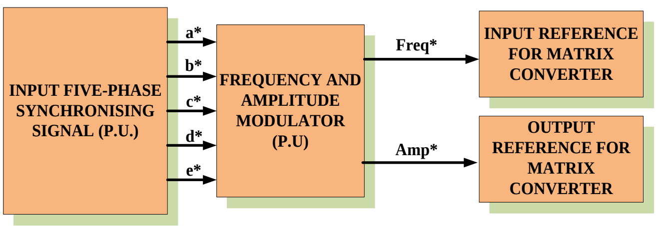

FIG. 2 CONTROL SCHEME FOR VARIABLE INPUT FIXED OUTPUT

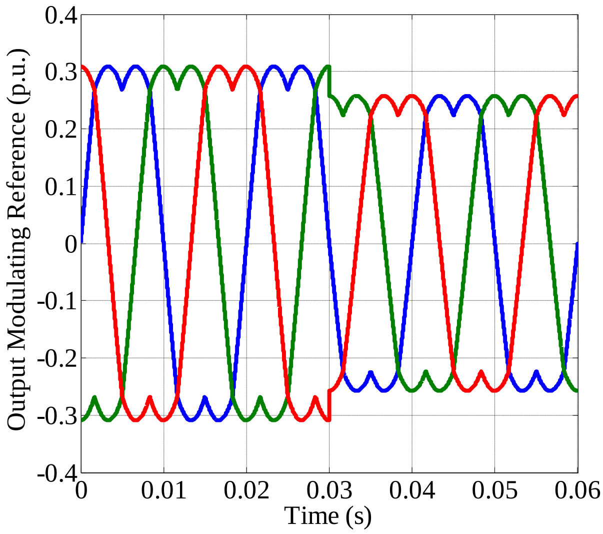

FIG. 3 OUTPUT MODULATING SIGNAL

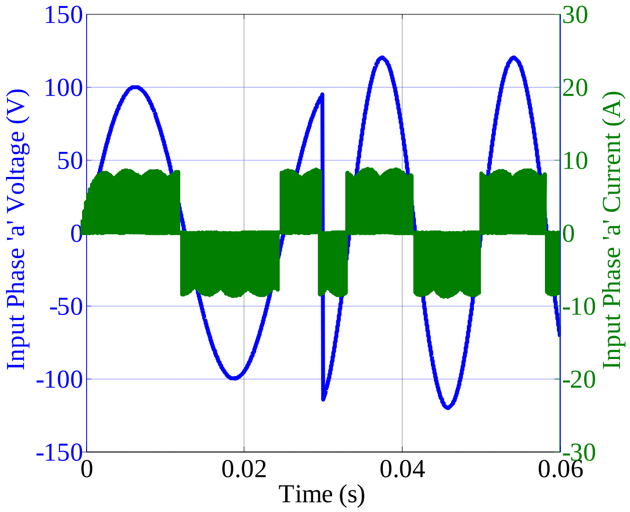

FIG. 4 INPUT PHASE VOLTAGE AND CURRENT

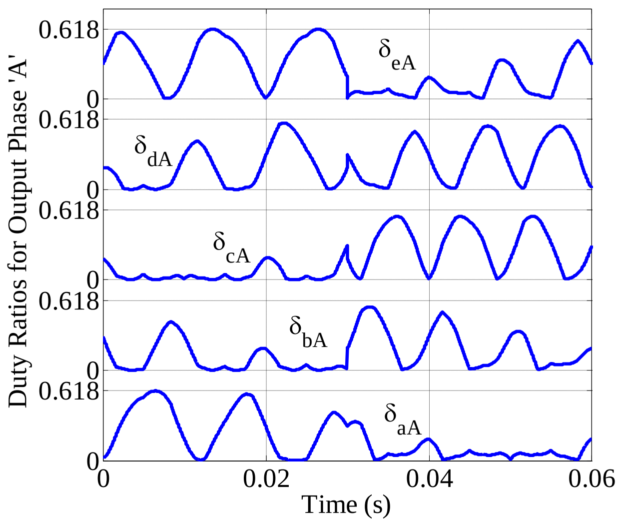

FIG. 5 OUTPUT DUTY RATIOS

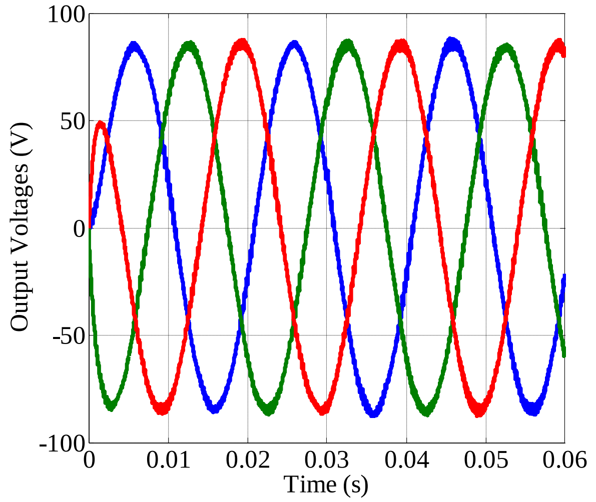

FIG. 6 FILTERED OUTPUT VOLTAGE

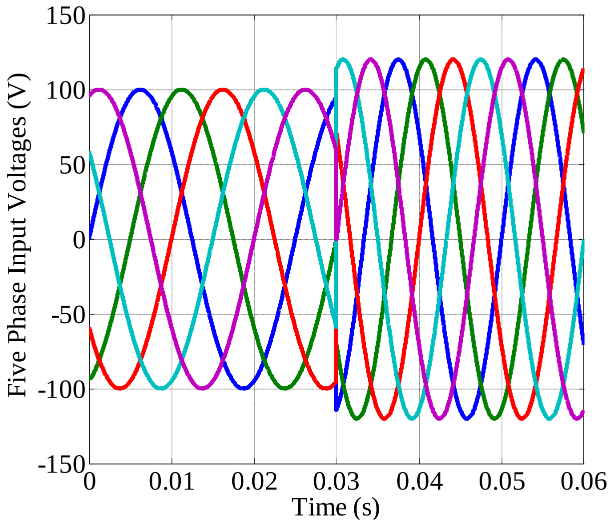

FIG. 7 FIVE-PHASE INPUT VOLTAGES

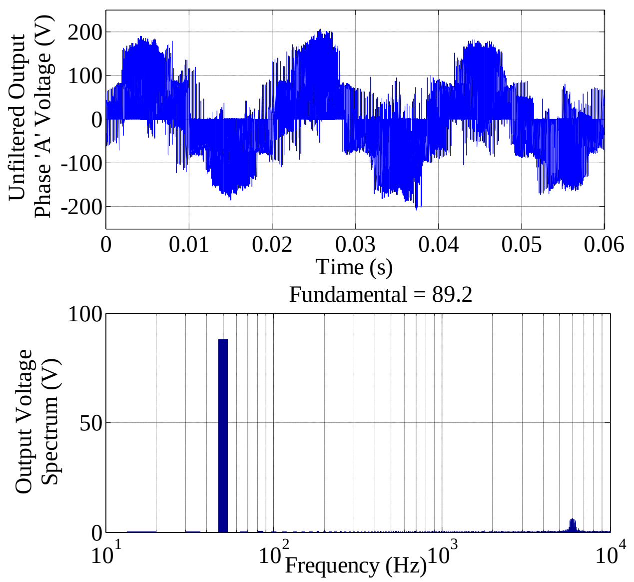

FIG. 8 SPECTRUM OF OUTPUT VOLTAGE

Experimental investigation

A prototype modular matrix converter is developed where input can be five phase and output is three phase. The proposed carrier based pulse width scheme is implemented for a five to three phase matrix converter. The five phase input is produced from a three to five phase inverter where the input is taken from grid through auto transformer. The five phase inverter output is passed through low pass filter. The block schematic of the experimental set-up is presented in Fig. 9. The power module is a bidirectional switch FIO 50-12BD from IXYS and is composed of a diagonal IGBT and fast diode bridge in ISOPLUS i4-PAC™.

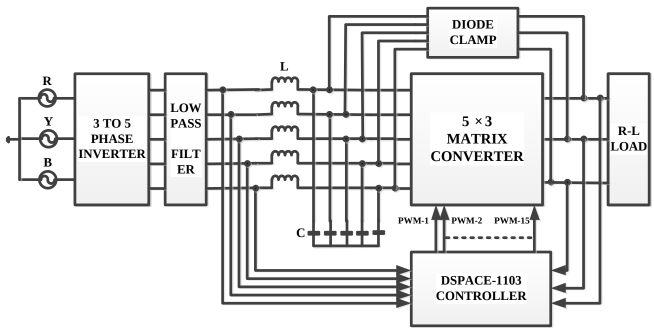

FIG. 9 BLOCK DIAGRAM OF EXPERIMENTAL SETUP

The voltage blocking capability of the device is 1200V and the current capacity is 50A. This comes in single chip with five output pins; four for the diode bridge and one for the gate drive of the IGBT. It controls bidirectional current flow by a single control signal. The advantage of this bidirectional power switch is the decreased number of IGBTs which is a major issue for multi-phase operation, but the major disadvantage is the higher conduction losses and the two-step commutation. Extra line inductances are used for safe operation during the overlapping of current commutation. Dead-time compensation is done along with snubbers and clamping circuit. The matrix converter consists of fifteen such bidirectional power switches. The control platform used is the DSPACE-1103 controller. Furthermore, the modulation code is written in MATLAB and is processed in the Dspace. Logical tasks, such as A/D and D/A conversion, gate drive signal generation, etc are accomplished by the powerful Dspace board. The Dspace-1103 board is able to handle up to 31 PWM signals. Clamping diodes are used for protection purposes.

The switching frequency of the bidirectional power switch of the matrix converter is fixed at 6 kHz. The value of input LC filter used for this configuration is 200 μH 10 A and 40 μF, 440V, respectively. The

frequency and amplitude of the three to five phase inverter input is maintained at 30 Hz and 100 V initially. A step change in the inverter output is also shown from its initial value to 45 Hz and 120 V. The output of the matrix converter is maintained at 50 Hz with constant voltage of 89 V which is shown in the fig. 10. A three-phase R-L load is connected at the output terminals of the matrix converter with R = 10 Ω and L = 30 mH.

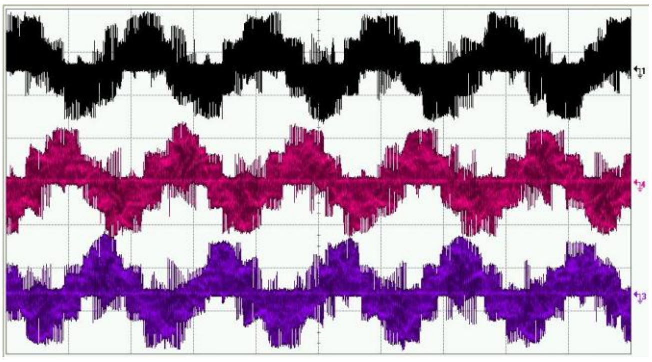

FIG. 10 OUTPUT VOLTAGES OF MATRIX CONVERTER (100 V, 10 MSEC/DIV)

Conclusion

The paper proposes modulation and control of a five-phase input and three-phase output direct ac-ac converter. The control objective is to obtain fixed voltage and fixed frequency three-phase output for variable voltage and variable frequency five-phase input. Simple carrier-based scheme is employed along with offset addition to enhance the output voltage magnitude. The output voltage magnitude is higher when compared to a conventional three-phase to three-phase matrix converter. The proposed technique can be modified to obtain variable voltage and variable frequency for the adjustable drive application too. The simulation and experimental results are reported in the paper to validate the proposed scheme.

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REFERENCES

[1] E.Levi, “Multi-phase Machines for variable speed applications”, *IEEE Trans. On Ind. Elect.* vol. 55, no. 5, pp. 1893-1909, May 2008.

[2] G.K. Singh, A. S. Kumar, and R.P. Saini, “Selection of capacitance for six-phase self excited induction generator for stand-alone renewable energy generation ” *Energy,* vol. 35, pp. 3273-3283, 2010.

[3] Ojo O, Davidson IE. PWM-VSI inverter-assisted stand-alone dual stator winding induction generator. IEEE Transactions on Energy Conversion 2000; 36 (6):1604e11.

[4] Basic D, Zhu JZ, Boardman G. Transient performance study of a brushless doubly fed twin stator induction generator. IEEE Transactions on Energy Conversion 2000; 18(3):400e8.

[5] Levy D. Analysis of a double-stator induction machine used for a variable speed/constant-frequency small-scale hydro/wind electric power generator. Electric Power Systems Research 1986; 11:205e23.

[6] Singh GK, Yadav KB, Saini RP. Modeling and analysis of multi-phase (sixphase) self-excited induction generator. In: Proceedings on IEEE conference of the eighth international conference on electrical machines and systems, ICEMS’05, vol. 3; 2005. 1922e1927.

[7] Singh GK, Yadav KB, Saini RP. Analysis of a saturated multi-phase (six-phase) self-excited induction generator. International Journal of Emerging Electric Power Systems 2006; 7(2):1e23.

[8] Singh GK. Modeling and experimental analysis of a self-excited six-phase induction generator for stand-alone renewable energy generation. Renewable Energy 2008; 33:1605e21.

[9] Singh GK, Yadav KB, Saini RP. Capacitive self-excitation in six-phase induction generator for small hydro power-an experimental investigation. In: Proceedings of IEEE conference on power electronics, drives and energy systems for industrial growth 2006 (PEDES 2006), New Delhi, December 12e15, 2006. pp. 1e6.

[10] Singh GK, Yadav KB, Saini RP. A self-excited six-phase induction generator for stand-alone renewable energy generation. In: Proceedings of IEEE international agean conference on electric machines, power electronics and electromotions, ACEMP’07, Bordrum, Turkey; 10e12 September 2007. pp. 690e695.

[11] Singh GK. Steady-state performance analysis of six-phase self-excited induction generator for renewable

energy generation. In: Proceedings of the 11th International Conference on Electrical Machines and Systems ICEMS2008, Wuhan, P.R. China; October 17e20, 2008. pp. 2255e2260.

[12] Singh GK, Senthil Kumar A, Saini RP. Performance evaluation of series compensated self-excited six-phase induction generator for stand-alone renewable energy generation. Energy 2010; 35:288e97.

[13] P. W. Wheeler, J. Rodriguez, J. C. Clare, L. Empringham, A. Weinstein, "Matrix converter : A technology review," *IEEE Trans. On Ind. Electron.*, vol. 49, no. 2, pp. 276 – 288, April 2002.

[14] Sun Yao, Su Mei, Gui Wei Hua, "One novel Variable-speed wind energy system based on PMSG and super sparse matrix converter ",Electrical Machines and Systems, 2008. ICEMS 2008. International Conference on Publication Year: 2008, pp. 2384 – 2389.

[15] Guoliang Yang, Huiguang Li, "Application of a matrix converter for PMSG wind turbine generation system ",Clean Electrical Power, 2009 International Conference on Digital Object Identifier: 10.1109/ICCEP.2009.5211991 Publication Year, 2009 , pp. 619 – 623.

[16] Pena, R., Cardenas, R., Reyes, E., Clare, J., Wheeler, P., "A Topology for Multiple Generation System With Doubly Fed Induction Machines and Indirect Matrix Converter ",Industrial Electronics, IEEE Transactions on Volume: 56 , Issue: 10 Digital Object Identifier: 10.1109/TIE.2009.2028353 Publication Year: 2009 , pp. 4181 – 4193.

[17] Mihret, M., Abreham, M., Ojo, O., Karugaba, S., "Modulation schemes for five-phase to three-phase AC-AC matrix converters ",Energy Conversion Congress and Exposition (ECCE), 2010 IEEE DOI: 10.1109/ECCE.2010.5618296 Publication Year: 2010 , pp. 1887 – 1893.

[18] Ojo, O., Abreham, M., Karugaba, S., Komolafe, O.A., "Carrier-based modulation of non-square multi-phase AC-AC matrix converters ",Industrial Electronics (ISIE), 2010 IEEE International Symposium on DOI:10.1109/ISIE.2010.5637634 Publication Year: 2010 , pp. 2141 – 2146.